STS-114 Engine Cut-off Sensor Anomaly Technical Consultation Report

November 3, 2005

NESC Request No. 05-045-E

TABLE OF CONTENTS

Volume I: Technical Consultation Report

Volume II: Appendices

List of Figures

Volume I: Technical Consultation Report

1.0 Authorization and Notification

The request to conduct a real-time consultation involving the Space Transportation System (STS)-114 Space Shuttle Main Engine (SSME) Engine Cut-off (ECO) sensor anomaly was submitted to the NASA Engineering and Safety Center (NESC) on July 14, 2005.

The authority to participate in a real-time consultation was approved by the NESC Review Board (NRB) in an out-of-board action on July 14, 2005.

A final report will be presented to the NRB on November 3, 2005.

2.0 Signature Page

Consultation Team Members

Timmy R. Wilson, KSC, Lead NESC Chief Engineer	Robert Kichak, GSFC NESC Discipline Expert for Avionics
Robert Cherney, GSFC Orbital Sciences Corporation	Eugene Ungar, JSC Deputy NESC Discipline Expert for Fluids
Steve Rickman, JSC	

3.0 Team Members, Ex Officio Members, and Consultants

Timmy R. Wilson, KSC	NESC Chief Engineer (NCE)
Robert Kichak, GSFC	NESC Discipline Engineer (NDE) for Avionics
Eugene Ungar, JSC	Deputy NDE for Fluids, Thermal, and Life Support
Robert Cherney, GSFC	Orbital Sciences Corporation
Steve Rickman, JSC	

4.0 Executive Summary

The NESC consultation team participated in real-time troubleshooting of the Main Propulsion System (MPS) Engine Cut-off (ECO) sensor system failures during STS-114 launch countdown. The team assisted with External Tank (ET) thermal and ECO Point Sensor Box (PSB) circuit analyses, and made real-time inputs to the Space Shuttle Program (SSP) problem resolution teams. Several long-term recommendations resulted. One recommendation was to conduct cryogenic tests of the ECO sensors to validate, or disprove, the theory that variations in circuit impedance due to cryogenic effects on swaged connections within the sensor were the root cause of STS-114 failures. This recommendation resulted in the initiation of a follow-on NESC independent technical assessment (ITA) entitled *ECO Sensor Reliability Testing* (NESC ITA number 05-098-E).

Although anomaly troubleshooting was extensive, the root cause of the failures observed during the first STS-114 tanking test and launch scrub was not identified. The most probable causes include an intermittent electrical connection within the Orbiter or ET wiring from the ECO PSB to the sensor and return, an intermittent high resistance or open circuit in the senor itself, or a thermally-induced intermittent failure internal to the PSB.

5.0 Consultation

The scope of this consultation was limited to real-time troubleshooting of the STS-114 ECO sensor problems. This consultation was considered a quick turnaround task and, therefore, no consultation plan was generated prior to this review.

6.0 Description of the Problem, Proposed Solutions, and Risk Assessment

The MPS ECO system consists of point-sensors installed in the ET liquid hydrogen (LH_2) tank and the Orbiter's liquid oxygen (LO_2) feedline. Point sensor electronics are designed to condition signals and to provide appropriate stimulation of the sensors and associated wiring and connectors. Refer to Figure 6.0-1 for an overall schematic.

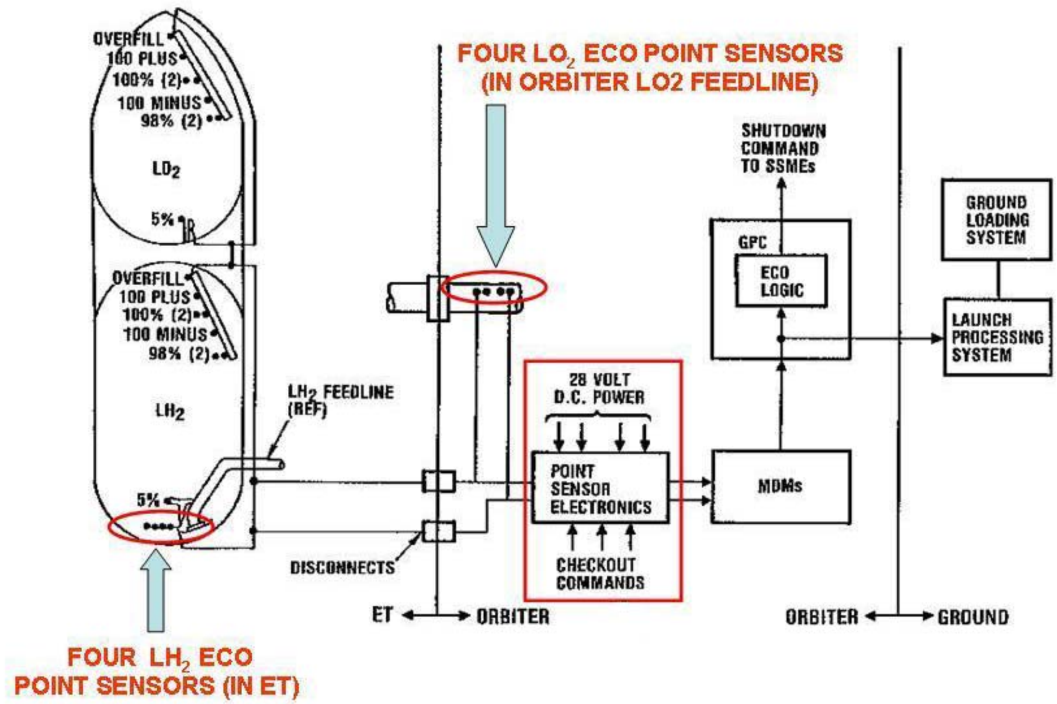

Figure 6.0-1. ECO and Liquid Level Sensors Block Diagram

The point sensor electronics interprets a low resistance at a sensor as the presence of cryogenic liquid, which provides a "wet" indication to the Multiplexer/De-Multiplexer (MDM) for use by on-board General Purpose Computers (GPCs) and the ground Launch Processing System (LPS). Conversely, a high resistance is interpreted as a "dry" indication. The point sensor electronics include circuitry suitable for pre-flight verification of circuit function and are designed to fail "wet". For example, an open circuit in the sensor, or an open or short in the signal path, will provide a "wet" indication to the MDM. The system is then activated and checked out during launch countdown and remains active during ascent.

An ECO sensor is depicted in Figure 6.0-2. The sensor consists of a platinum wire sensing element mounted on an alumina Printed Wiring Board (PWB) and is encased in an aluminum housing. The sensing element acts as a variable resistance which changes on exposure to cryogenic liquid. This resistance variation is detected by post-sensor (signal conditioning) electronics and is used to generate either a “wet” or “dry” indication as noted above.

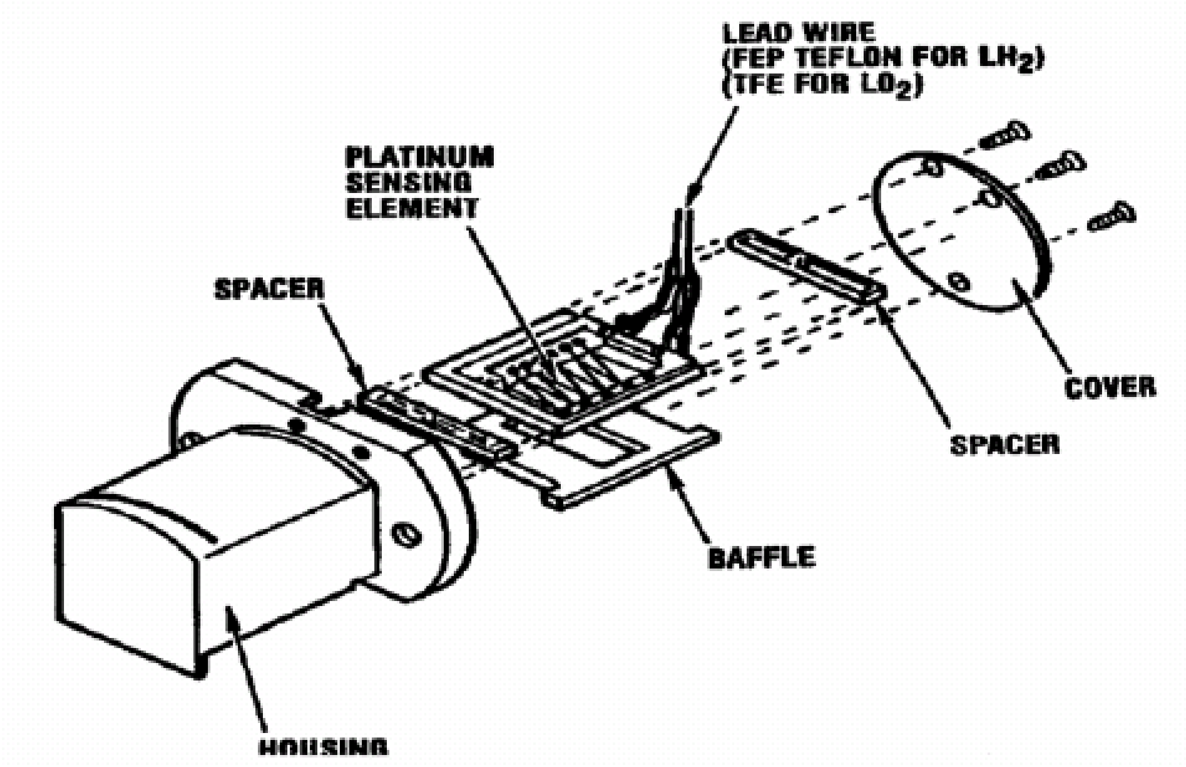

Figure 6.0-2. ECO Sensor System Overview

The ECO system is designed to protect the Space Shuttle Main Engines (SSMEs) from catastrophic failure due to propellant depletion. Flight software is coded to check for the presence of “wet” indications from the sensors within 8 to 12 seconds of SSME shutdown. The software rejects the first “dry” indication observed from any of the ECO sensors, but the presence of at least two more “dry” indications will result in a command to shutdown the SSMEs (i.e., “dry” indications from two of four “good” sensors are required for SSME shutdown). Early SSME shutdown would probably lead to a contingency Trans-Atlantic (TAL) abort. A failed “wet” indication cannot be detected. The system is designed so that LO_2 depletion should occur first. However, a failure “wet” indication of three of the four LH_2 sensors, coupled with an SSME problem that results in early LH_2 depletion, could result in catastrophic failure of a SSME. Failure probability is considered remote, but would almost certainly be catastrophic to the flight vehicle. The system architecture addresses redundancy with one point sensor box containing four groups of sensor conditioner circuit cards. Each card can accommodate one hydrogen and one oxygen sensor. Each card group has its own power converter and one sensor conditioner card from each group services a pair of ECO sensors (again, one hydrogen and one oxygen). Wiring for each of the eight ECO sensors is split into one of two groups of sensors which are routed through separate Orbiter / ET monoball connections."

During the first STS-114 tanking test, LH_2 ECO-4 failed to transition from “wet” to “dry” when subjected to simulated “dry” commands. During de-tank, the same sensor failed to transition to “dry” when the liquid level dropped below the sensor, but did transition several minutes later. After de-tank, LH_2 ECO-3 indicated “wet” for approximately 90 minutes, then returned to the “dry” state. Extensive troubleshooting conducted after the failures did not isolate the cause and problems did not recur during the second STS-114 tanking test. During the first STS-114 launch attempt, ECO-2 failed to transition from “wet” to “dry” when the “dry-when-wet” state was commanded. This sensor remained “wet” until about three hours into de-tank boil-off when it transitioned to “dry.”

The NESC consultation team participated in subsequent troubleshooting.

7.0 Data Analysis

The NESC consultation team did not conduct independent test or analysis during the course of this consultation, but participated with the SSP teams in real-time troubleshooting of the STS-114 ECO sensor problems. Section 8.0 provides the team's findings, observations, and recommendations.

Troubleshooting after the first launch attempt was impaired by the inability to recreate the anomalous system behavior. It only occurred when the vehicle was fueled and ready for launch. While a change was implemented to facilitate troubleshooting by swapping ECO sensors between two PSB signal conditioner channels, the overall effort was constrained by a programmatic requirement to maintain the vehicle in a launch-ready configuration.

8.0 Findings, Observations and Recommendations

8.1 Findings

F-1. STS-114 troubleshooting did not isolate the root cause of the ECO sensor failures.

F-2. The SSP does not test ECO sensors prior to launch countdown in LH_2 at -423 deg F, but tests them in liquid nitrogen (LN_2) at -320 deg F.

F-3. Isolation and continuity checks of PSB connectors are not routinely performed.

F-4. PSB transient suppressor electronics are not subjected to routine functional tests.

F-5. An Electromagnetic Interference (EMI) induced failure observed during testing of modified PSB electronics was reproduced at the NASA Shuttle Logistics Depot (NSLD). The failure was traced to circuit differences between a flight unit and the modified PSB under test, which was removed from the Shuttle Avionics Integration Laboratory (SAIL). It was initiated by non-standard sensor test resistance values and has been explained by circuit analysis and testing.

F-6. PSB electronics were subjected to stability testing in the past for several hours with no heat-sinking and no temperature monitoring. While current practice is to test the boxes on a heat-sink, latent effects of the earlier testing are unknown.

F-7. PSB electronics have been the subject of a number of workmanship issues including poor solder joints, lack of solder on some connections, and discrepant flex ribbon assemblies (the flex ribbon assemblies have been especially problematic, according to NSLD personnel). Extent of remaining workmanship problems is unknown.

8.2 Observations

O-1. While the root cause of the STS-114 failure was not identified, two probable causes surfaced including an intermittent open somewhere in the wiring from the PSB to the sensors and return, an intermittent high resistance or open of the sensor itself, or a thermally-induced intermittent failure internal to the PSB. To minimize flight risk, the SSP implemented a set of real-time screens during launch countdown to help detect and isolate a failure. The SSP determined, and the NESC concurred, that launch with a single failed ECO sensor was acceptable providing the problem could be isolated to the one sensor/electronics channel which failed during the first STS-114 launch attempt.

Sensor 2 and 4 PSB inputs were switched to facilitate real-time troubleshooting and problem isolation during launch countdown, but the failure did not recur.

O-2. There are a number of open questions pertaining to the ECO sensor. The sensors are not screened at LH_2 temperatures prior to installation as noted in Finding F-1. This may affect their reliability. The design incorporates swaged terminals and stainless steel surface passivation which may also contribute to intermittent cold opens.

O-3. Since multiple power grounds enter the PSBs, they must be shown to be isolated through routine continuity and isolation tests performed at the interface connectors. The chassis continuity connections need to be verified, as do the transient suppressors installed across the sensor lines and 28-volt bus in the power converters.

O-4. Transient suppressors used in this design may be incorrectly sized. Review of the PSB power converter schematic (1500067, revision T) shows the Transient Voltage Suppressors (TVS) to be back-to-back 1N5611s. According to the data sheet for this part, it begins to zener at 43.7 volts and clamps at 63.5 volts at peak surge current. The IC1 and IC2 op-amps are 741s and are directly across the unfiltered 28-volt supply in the drawings reviewed (1500062-005 revision D). According to the data sheet, the LM741 absolute maximum Vcc rating is $\pm$22 volts, or 44 volts total. It appears that input voltage surges, particularly strong ones, may be able to overvoltage stress the op-amps if these schematics are correct.

O-5. A problem with loose card guides noted during troubleshooting of the STS-114 ECO problems has not been fully resolved. The guides in at least one PSB were re-glued (S/N 110). However, when the unit was disassembled due to a card guide lug short circuit, the guides were found to have again de-bonded. The guides are necessary to help dissipate a relatively high heat load (over 100 watts of waste heat) and are a potential source of internal contamination when de-bonded due to the potential for liberation of copper beads incorporated in the epoxy adhesive to improve thermal conductivity.

O-6. There are a number of lingering issues with parts used in the PSBs. Government-Industry Data Exchange Program (GIDEP) Alert BZ-A-80-01D covered many Fairchild Semiconductor part numbers and Lot Date Codes (LDC). Parts considered suspect during the STS-114 troubleshooting were researched (LDC 7830 2N2222), but the PSBs contain other transitors including 2N2907 and 2N2219, which may also be covered by the Alert if they were manufactured by Fairchild and are in the LDC range of concern.

O-7. Specific issues with two of the PSB's tested during the STS-114 troubleshooting have yet to be resolved. The PSB S/N 112 power converter has been noisy. This may be related to power converter instability or limit cycle regulation. Age may affect capacitor properties that can also possibly affect stability. This should be investigated further to ensure high reliability. In addition, the potential for copper path damage between the signal conditioner card circuitry and electrical connector in PSB S/N 111 should be assessed.

O-8. Test method CS116 has replaced CS06 as a method of testing EMI / EMC compliance. Although CS116 is a less-stringent test, unlike CS06 it applies to signal lines as well as power lines. The Point Sensor Box has been designed with bandwidth-limiting networks only on the power leads. Suspicion remains that the signal lines were never designed to be subjected to high input levels and CS116 testing could be over-stressing the circuitry, particularly the transient suppressors intended to provide ESD protection.

8.3 Recommendations

R-1. Conduct a series of cryogenic tests to determine whether reliability issues exist with the ECO sensors. These tests should address issues surrounding the use of staked connections and passivated stainless steel surfaces.

R-2. Modify PSB pre-flight testing and incorporate checkout of transient suppressor electronics and verification of multiple power grounds.

R-3. Verify CS116 EMI / EMC testing does not overstress PSB input circuitry.

R-4. Complete a review of the PSB circuit design and ensure transient suppressor electronics are properly sized and that all parts have been screened for any GIDEP-related issues.

R-5. Ensure all PSBs have been screened for potential workmanship and assembly issues, including loose card guides and damaged flex-ribbon assemblies, and that such problems have been eliminated to the extent possible.

R-6. Determine whether power-on testing of PSB electronics without a heat-sink may have resulted in component overstress and, if so, what components are likely to be affected and how failure of those components may manifest itself in flight.

R-7. Isolate the cause of PSB S/N 112 power converter noise and inspect PSB S/N 111 for copper path damage between the signal conditioner card circuitry and electrical connector.

9.0 Lessons Learned

Given the amount of time available for the STS-114 ECO real-time troubleshooting, the NESC's contribution was limited to assembly of a knowledgeable team of experts who participated in the real-time troubleshooting efforts. No significant lessons-learned were generated.

10.0 Definition of Terms

Corrective Actions	Changes to design processes, work instructions, workmanship practices, training, inspections, tests, procedures, specifications, drawings, tools, equipment, facilities, resources, or material that result in preventing, minimizing, or limiting the potential for recurrence of a problem.
Finding	A conclusion based on facts established during the assessment/inspection by the investigating authority.
Lessons Learned	Knowledge or understanding gained by experience. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure. A lesson must be significant in that it has real or assumed impact on operations; valid in that it is factually and technically correct; and applicable in that it identifies a specific design, process, or decision that reduces or limits the potential for failures and mishaps, or reinforces a positive result.
Observation	A factor, event, or circumstance identified during the assessment/inspection that did not contribute to the problem, but if left uncorrected has the potential to cause a mishap, injury, or increase the severity should a mishap occur.
Passivation	The process of making a material "passive" in relation to another material prior to using the materials together. In the context of corrosion, passivation is the spontaneous formation of a hard surface film which inhibits further corrosion. Under normal conditions of pH and oxygen concentration, passivation is seen in such materials as aluminum, stainless steel, titanium, and silicon.
Problem	The subject of the technical assessment/inspection.
Requirement	An action developed by the assessment/inspection team to correct the cause or a deficiency identified during the investigation. The requirements will be used in the preparation of the corrective action plan.

Root Cause	Along a chain of events leading to a mishap or close call, the first causal action or failure to act that could have been controlled systemically either by policy/practice/procedure or individual adherence to policy/practice/procedure.

11.0 Minority Report (Dissenting Opinions)

There were no dissenting opinions during this consultation.

Volume II: Appendices

Appendix A. ITA/I Request Form (NESC-PR-003-FM-01)

NASA Engineering and Safety Center
Request Form

Submit this ITA/I Request, with associated artifacts attached, to: nrbexecsec@nasa.gov, or to NRB Executive Secretary, M/S 105, NASA Langley Research Center, Hampton, VA 23681

Section 1: NESC Review Board (NRB) Executive Secretary Record of Receipt		
Received (mm/dd/yyyy h:mm am/pm) 7/14/2005 12:00 AM	Status: New	Reference #: 05-045-E
Initiator Name: John Muratore	E-mail: john.f.muratore@nasa.gov	Center: JSC
Phone: (281)-483-4467, Ext _____	Mail Stop: MS	
Short Title: STS-114 Engine Cut-off Sensor Anomaly		
Description: Support the Space Shuttle Program efforts to resolve the STS-114 Engine Cut-Off (ECO) sensor anomaly. Three people from the NESC are actively engaged: Bob Kickak working the ECO sensor electronics analysis, Gene Ungar, participating with the ET thermal modeling team and Steve Rickman enlisted by Gene to participate on the sensor electronics thermal analysis team.		
Source (e.g. email, phone call, posted on web): Verbal to Ralph Roe		
Type of Request: Consultation		
Proposed Need Date:		
Date forwarded to Systems Engineering Office (SEO): (mm/dd/yyyy h:mm am/pm):		
Section 2: Systems Engineering Office Screening		
Section 2.1 Potential ITA/I Identification		
Received by SEO: (mm/dd/yyyy h:mm am/pm): 7/14/2005 12:00 AM		
Potential ITA/I candidate? ☒ Yes ☐ No		
Assigned Initial Evaluator (IE): Tim Wilson		
Date assigned (mm/dd/yyyy): 7/14/2005		
Due date for ITA/I Screening (mm/dd/yyyy):		
Section 2.2 Non-ITA/I Action		
Requires additional NESC action (non-ITA/I)? ☐ Yes ☐ No		
If yes:		
Description of action:		
Actionee:		
Is follow-up required? ☐ Yes ☐ No If yes: Due Date:		
Follow-up status/date:		
If no:		
NESC Director Concurrence (signature):		
Request closure date:		

NESC Request Form
NESC-PR-003-FM-01, v1.0

Page 1 of 3

Section 3: Initial Evaluation		
Received by IE: (mm/dd/yyyy h:mm am/pm):		
Screening complete date:		
Valid ITA/I candidate? ☐Yes ☐ No		
Initial Evaluation Report #: NESC-PN-		
Target NRB Review Date:		
Section 4: NRB Review and Disposition of NCE Response Report		
ITA/I Approved: ☐Yes ☐ No	Date Approved:	Priority: - Select -
ITA/I Lead: , Phone ( ) - , x		
Section 5: ITA/I Lead Planning, Conduct, and Reporting		
Plan Development Start Date:		
ITA/I Plan # NESC-PL-		
Plan Approval Date:		
ITA/I Start Date	Planned:	Actual:
ITA/I Completed Date:		
ITA/I Final Report #: NESC-PN-		
ITA/I Briefing Package #: NESC-PN-		
Follow-up Required? ☐Yes ☐ No		
Section 6: Follow-up		
Date Findings Briefed to Customer:		
Follow-up Accepted: ☐Yes ☐ No		
Follow-up Completed Date:		
Follow-up Report #: NESC-RP-		
Section 7: Disposition and Notification		
Notification type: - Select -	Details:	
Date of Notification:		
Final Disposition: - Select -		
Rationale for Disposition:		
Close Out Review Date:		

Form Approval and Document Revision History

Approved: ______________________________ __________
NESC Director Date

Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Principal Engineers Office	29 Jan 04

Appendix B. List of Acronyms

ECO	Engine Cutoff
EMI	Electromagnetic Interference
ET	External Tank
GIDEP	Government-Industry Data Exchange Program
GPC	General Purpose Computer
ITA	Independent Technical Assessment
JSC	Johnson Space Center
KSC	Kennedy Space Center
LaRC	Langley Research Center
LCC	Launch Commit Criteria
LDC	Lot Date Codes
LH_2	Liquid Hydrogen
LN_2	Liquid Nitrogen
LO_2	Liquid Oxygen
LPS	Launch Processing System
MPS	Main Propulsion System
MDM	Multiplexer/De-Multiplexer
NASA	National Aeronautics and Space Administration
NCE	NESC Chief Engineer
NDE	NESC Discipline Engineer
NESC	NASA Engineering and Safety Center
NSLD	NASA Shuttle Logistics Depot
NRB	NESC Review Board
OMRSD	Orbiter Maintenance and Requirements Specification Documents
PSB	Point Sensor Box
PWB	Printed Wiring Board
SAIL	Shuttle Avionics Integration Laboratory
SPICE	SSP with Integrated Circuit Emphasis
SSME	Space Shuttle Main Engine
SSP	Space Shuttle Program
STS	Space Transportation System
TAL	Trans-Atlantic
TVS	Transient Voltage Suppressor

Approval and Document Revision History

Approved:	Original signed on file	11/8/05
	NESC Director	Date

Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	NESC Chief Engineer's Office	